Graduate School of Creative Science and Engineering
Waseda University

博 士 論 文 概 要
Doctoral Thesis Synopsis

論 文 題 目
Thesis Theme

Reliability Estimation of RC Structures Considering the Non-uniformity of Steel Corrosion Distribution
鉄筋腐食分布の不均一性を考慮したRC 構造物の信頼性評価

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The deterioration of RC structures due to corrosion of their rebars is a crucial issue for the construction owners and researchers. Reinforcement corrosion affects both the serviceability and structural performance of RC structures, causing an increase in their life-cycle cost due to maintenance actions and repair interventions. Corrosion of steel reinforcement is spatially distributed over RC structures due to several factors such as different environmental exposure, concrete cover, and concrete quality, among others. Ignoring the effect of spatial variability is a drastic simplification for the prediction of the remaining service life of RC structures. Hence, it is very important to model the spatial variability in steel corrosion and incorporate its effect into a prediction method for the reliability analysis of RC structures.

To achieve this goal, there is a need to experimentally investigate the important factors influencing the spatial variability associated with steel corrosion and their effects on the structural performance of corroded RC structures. Moreover, due to the highly non-uniform steel corrosion over RC structures, the distribution of parameters for quantifying the spatial variability can be considered as stochastic process. Gumbel distribution has been widely used to model the spatial variability associated with steel corrosion since the local maxima of steel cross-section loss is the most relevant parameter determining the performance of corroded RC structures. To assess the stochastic behavior of RC structure with random parameters, one of the applicable solutions is to incorporate probability theory with deterministic FE method, which is becoming robust enough to estimate the failure probability of structural members. Therefore, it is important to conduct the reliability assessment of corroded RC beam incorporating the random field with FE method.

In this study, experimental research is conducted to examine the effects of main parameters (i.e. current density, concrete cover, rebar diameter, and fly ash) on the spatial variability associated with steel weight loss, corrosion crack, and structural behavior of accelerated-corrosion RC beams. A novel procedure is proposed to assess the reliability of corroded RC beam considering non-uniform corrosion of rebars in Monte Carlo simulation incorporated with FE method. This dissertation consists of four parts. First part reveals the background associated with the effect of corrosion on the long-term structural performance and the importance of considering spatial variability of steel corrosion in the probabilistic life-cycle performance assessment of corroded RC structures. The second part explains the experiment investigation to study the effects of main factors on the spatial variability of steel corrosion. The spatial distribution of corrosion of rebar embedded in the beams at different corrosion levels was monitored and quantified using X-ray and digital image processing technique. In the third part, the statistical data based on Gumbel distribution was derived from the experimental data and incorporated in a probabilistic model to approximately estimate the spatial steel corrosion. Meanwhile, the effect of current density on the spatial variability of steel corrosion and Gumbel distribution parameters is presented and discussed. A procedure is proposed to assess the reliability of corroded RC beams incorporating Monte Carlo simulation with FE method. Finally, the fourth part highlights the achievements in this study, and proposes some suggestions for future works according to the limitation in this study. According to the objectives, eight chapters are included in this dissertation.

In chapter 1, background of this research was presented, followed by the objectives of present research. The corrosion of steel reinforcement in concrete is spatially distributed over RC structures due to several factors such as different environmental exposure, concrete cover, and concrete quality, among others. Hence, it is vital importance to identify the factors affecting the spatial variability associated with steel corrosion. Meanwhile, it is also important to model the spatial variability in steel corrosion and incorporate its effect into a prediction method for the reliability analysis of RC structures. Three primary objectives are: (1) the experimental investigation of the effects of main factors (i.e. current density, cover, rebar diameter and fly ash) on the spatial variability of steel corrosion, (2) probabilistic model for modeling the spatial variability of steel corrosion, and (3) a reliability assessment procedure of corroded RC beams considering the spatial variability of steel corrosion.

In chapter 2, systematic literature reviews are conducted on mechanism of steel corrosion in concrete, the effects of steel corrosion on the structural performance of RC structures, accelerated corrosion test method used in the previous studies and the start-of-art probabilistic models for modeling the spatial variability of steel corrosion in reliability assessment of corroded RC structures.

In chapter 3, an experimental program is presented. Experiments were conducted to study the effects of current density, cover, rebar diameter, and fly ash on the spatial variability associated with steel weight loss in corroded RC beams and their flexural behavior. The spatial variability of steel weight loss of rebar embedded in the beams at different corrosion levels was monitored and quantified using X-ray and digital image processing technique. The measurement method of spatial distribution associated with surface crack width at different corrosion levels was also presented. In the accelerated corrosion test, the constant current was applied to generate current density of 10 $\mu A/cm^2$, 50 $\mu A/cm^2$, 100 $\mu A/cm^2$, 200 $\mu A/cm^2$, and 500 $\mu A/cm^2$. To compare the spatial steel corrosion patterns investigated in this study, other experimental results from the previous studies with current density of 1000 $\mu A/cm^2$ was also used. Covers of 10 mm and 20 mm were used with rebar diameters of 13 mm and 19 mm. One specimen with 30% cement replaced by fly ash was cast to study the effect of fly ash on the spatial variability associated with steel corrosion and crack width.

In chapter 4, the major findings of experimental studies are given and discussed. The absolute error of estimated steel weight loss using image processing technique was found to be less than 1.5%, compared with the the actual measured steel weight loss. It proves that the steel weight loss measured by X-ray technique has a good degree of accuracy. Based on the experimental results, it can be noted that the spatial variability in steel weight loss is dependent on the impressed current density. The rebar with current density of 10 $\mu A/cm^2$ has a large corrosion pits intensifying at small region. The corrosion in specimens with higher current density (≥100 μA/cm^2) fluctuated with several peaks over the length of rebar. Moreover, based on the statistic results of experiment, it suggests a significant implication that the stochastic field of spatial steel corrosion which is generated using the statistical data of accelerated steel corrosion in the laboratory is significantly affected by the impressed current density.

In chapter 5, an FE model is proposed and the FE analysis results are validated by the experimental results of four-point bending test. It shows that FE model can provide the good agreement with the experimental results independent of the element length.

In chapter 6, a probabilistic model for structural performance assessment of corroded RC beam is described. A factor R_{swl} (i.e. the ratio of local maximum steel weight loss to mean steel weight loss) is proposed to quantify the spatial variability associated with steel corrosion. The statistical data based on Gumbel distribution was derived from the experimental data and incorporated in a probabilistic model to approximately estimate the spatial steel corrosion. The effect of current density on the load capacity of corroded RC beam is presented by using probabilistic and FE method. The comparison between the distribution of yield load capacity shows that the results of yield load capacity using the Gumbel distribution parameters with low current density are lower and more scattered than that using the parameters with high current density. These results suggest that the level of current density has a substantial influence on Gumbel statistics and structural performance of corroded RC beams.

In chapter 7, the author proposes a procedure for reliability assessment of corroded RC structures using FE method coupled with random fields considering the spatial variability associated with steel corrosion. An illustrated example is presented. A simply-supported RC beam reinforced by a single rebar affected by corrosion is considered. The effect of modeled non-uniform steel corrosion associated with different element lengths and correlation of rebar elements on the reliability of aging RC structures is evaluated and discussed. Failure probability of the RC beam is influenced by the element length and correlation of R_{swl}. Ignoring the correlation of R_{swl}, it may lead to overestimate the failure probability of corroded RC structures. The smaller element length will lead to a higher probability of failure when the correlation is neglected.

In chapter 8, conclusions are drawn based on the experimental and computational works and suggestions for further research are presented. Among the experimental parameters, current density has a significant effect on Gumbel distribution parameters and structural behavior of the RC beams. The distribution of R_{swl} associated with low current density used (≤ 50 μA/cm^2) has a significantly larger scale parameter than the specimens with a large current density (≥100 μA/cm^2). Using the Gumbel distribution parameters obtained by the experimental data with higher current density may underestimate the non-uniformity of corrosion distribution. This can lead to an overestimation of load capacity in the evaluation of corroded RC structures.

早稲田大学　博士（工学）　学位申請　研究業績書

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a. Academic papers	**1. Academic journals (Peer-reviewed)** ○ (1) Mingyang Zhang, Huijuan Song, Sopokhem Lim, Mitsuyoshi Akiyama, Dan M. Frangopol. Reliability estimation of corroded RC structures based on spatial variability using experimental evidence, probabilistic analysis and finite element method, Engineering Structures, Vol.192, pp.30-52, Aug. 2019. (2) Mingyang Zhang, Weilun Wang, Mitsuyoshi Akiyama. Stress-strain modeling of confined concrete using artificial neural networks, Proceedings of the Japan Concrete Institute, Vol.40, No.2, pp.121-126, Jul. 2018. (3) Mingyang Zhang, Mina Shintani, Jiyu Xin, Mitsuyoshi Akiyama. Prediction of corrosion-induced crack width distribution: comparing 3D FE and experimental results, Proceedings of the Japan Concrete Institute, Jul. 2020. (In printing) (4) Weilun Wang, Mingyang Zhang, Yun Tang, Xiaogang Zhang, Xiaobo Ding. Behaviour of high-strength concrete columns confined by spiral reinforcement under uniaxial compression, Construction and Building Materials, Vol.154, pp.496-503, Nov. 2017. (5) Mingyang Zhang, Xin Tang, Weilun Wang. Study on axial compression test of fiber reinforced ultra-high strength concrete column confined by high-strength reinforcement, Advances in Computer Science Research, Vol.71, pp.234-238, Jan. 2017. **2. Conference articles (Peer-reviewed)** ○ (6) Mitsuyoshi Akiyama, Dan M. Frangopol, Mingyang Zhang. Spatial variability of rebar corrosion and performance evaluation of corroded RC structures using probabilistic analysis and finite element method. International Probabilistic Workshop (IPW2020); Sept. 2020, Guimarães, Portugal. (In printing) ○ (7) Mingyang Zhang, Sopokhem Lim, Mitsuyoshi Akiyama, Dan M. Frangopol. Reliability assessment of RC bridge girders with non-uniform steel corrosion using probabilistic analysis and finite element method. 10th International Conference on Bridge Maintenance, Safety and Management (IABMAS2020); Apr. 2021, Sapporo, Japan. (In printing) (8) Sopokhem Lim, Mingyang Zhang, Mitsuyoshi Akiyama. Effects of non-uniform steel corrosion on the structural behavior of RC beams. 10th International Conference on Bridge Maintenance, Safety and Management (IABMAS2020); Apr. 2021, Sapporo, Japan. (In printing) (9) Jiyu Xin, Mingyang Zhang, Mitsuyoshi Akiyama, Dan M. Frangopol, Jianzhong Pei. Probabilistic life-cycle cost design of asphalt pavement based on machine learning approach, The Seventh International Symposium on Life-Cycle Civil Engineering (IALCCE2020); Oct. 2020, Shanghai, China. (In printing)

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c. Lectures	○ (10) Mingyang Zhang, Sopokhem Lim, and Mitsuyoshi Akiyama, Dan M. Frangopol. Reliability estimation of RC structures using FEM coupled with random fields considering spatial variability of steel corrosion, 7th International Symposium on Reliability Engineering and Risk Management (ISRERM2020); Jun. 2020, Beijing, China. (In printing) ○ (11) Mingyang Zhang, Sopokhem Lim, Chengzhi Zhang, Mitsuyoshi Akiyama. Reliability estimation of corroded RC beams considering the spatial variability associated with steel corrosion, The Ninth Japan Conference on Structural Safety and Reliability (JCOSSAR2019); pp.33-34, Oct. 2019, Tokyo, Japan. ○ (12) Sopokhem Lim, Mingyang Zhang, Mitsuyoshi Akiyama. Influences of current density on the spatial steel corrosion and reliability of corrosion-affected RC beams. Proceedings of the *fib* Symposium 2019, Concrete - Innovations in Materials, Design and Structures; pp.2091-2097, May 2019, Krakow, Poland. ○ (13) Mingyang Zhang, Sopokhem Lim, Mitsuyoshi Akiyama. Dan M. Frangopol. Modeling spatial variability of steel corrosion using Gumbel distribution. 13th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP13); May 2019, Seoul, South Korea. **3. Academic conference presentations** (1) Mingyang Zhang. Reliability estimation of corroded RC beams considering the spatial variability associated with steel corrosion. The Ninth Japan Conference on Structural Safety and Reliability (JCOSSAR2019), Tokyo, Japan, Oct. 2019. (2) Mingyang Zhang. Modeling spatial variability of steel corrosion using Gumbel distribution. 13th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP13), Seoul, South Korea, May 2019. (International conference) (3) Mingyang Zhang. Stress-strain modeling of confined concrete using artificial neural networks. JCI Annual Convention 2018. Japan Concrete Institute, Kobe, Japan, Jul. 2018.